VOLCANIC HAZARDS IN THE HAWAIIAN ISLANDS

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ABSTRACT

Volcanic eruptions have built the Hawaiian Islands, and similar eruptions in the future will affect many areas in them, especially on Kilauea and Mauna Loa Volcanoes on the Island of Hawaii. Some of those eruptions will endanger people and property. Hazards that result directly from eruptions include lava flows, tephra falls, volcanic gases, and pyroclastic surges. Less direct hazards associated with eruptions include ground fractures and subsidence, earthquakes, and tsunamis.

The Islands of Hawaii and Maui have been subdivided on maps, for some kinds of hazards, into various zones of differing magnitude of hazard. These hazard-zone maps can be used for making land-use decisions before eruptions occur and for responding to actual or threatened eruptions. Hazard-zone maps for earthquakes and tsunamis are not included in this report; however, earthquakes of both volcanic and nonvolcanic origin can affect extensive areas in the islands, and tsunamis can be highly damaging in narrow coastal zones.

Because most volcanic events cannot be effectively controlled, volcanic hazards are best avoided by land-use planning before eruptions occur and by evacuation when they do occur. Mitigation measures to reduce effects from lava flows can be effective, at least temporarily, but such measures are generally more effective for some other hazards such as tephra falls and volcanic gases.

INTRODUCTION

All the Hawaiian Islands have been built by volcanic eruptions over a period of millions of years. Similar eruptions have continued into historical time on the islands of Hawaii and Maui and undoubtedly will occur in the future, especially on Kilauea and Mauna Loa Volcanoes. Most Hawaiian eruptions form lava flows that endanger chiefly property; explosive eruptions are relatively rare but are more likely to threaten people. As intensive land development expands toward areas of relatively high hazard, the threat to life and property will increase accordingly.

This report discusses the characteristics, frequency, location, and extent of various hazardous phenomena typical of Hawaiian volcanoes, assesses the likely future extent, frequency, and relative severity of these phenomena, and shows distribution of some hazards on hazard-zone maps. Although they have distinct limitations, these maps can be useful for planning long-range mitigation of volcanic hazards and for organizing short-term response to eruptions.

The character of volcanic eruptions in Hawaii has been described at length in many previous reports (for example, Macdonald and Abbott, 1970; Macdonald, 1972) and is treated at length elsewhere in this volume. Brief descriptions of volcanic activity in this assessment are intended to emphasize certain characteristics that can help the public and public officials to understand volcanic hazards and ways of mitigating them. Hazards resulting from eruptions that bring rock materials to or above the ground surface are here termed direct hazards. Hazards termed indirect are events that accompany such eruptions, or are secondary effects of eruptions, or result from movement of magma that does not reach the ground surface.

The term hazard in this report refers either to a hazardous event or to its products; examples are an explosive eruption or a lava flow. The term risk refers to the likelihood of losses to people, such as the loss of life, homes, or productive land. Volcanic hazards in the nearly uninhabited upper part of the east rift zone of Kilauea, for example, are of about the same frequency and severity as those in the lower, more highly populated part of the rift zone. Risk, however, is much higher in the lower part because of its greater population and more intensive land use. The potential hazards from volcanic eruptions in the islands will remain about the same in the foreseeable future, but increased risk from those eruptions will accompany growth in population and economic development.

HAWAIIAN VOLCANIC ACTIVITY

The Hawaiian Islands (fig. 22.1) lie at the southeastern end of a largely submerged volcanic chain about 6,000 km long, which extends from the Emperor Seamounts to the Island of Hawaii (Dalrymple and others, 1973). This chain consists of volcanoes that are progressively younger toward the southeast; Kilauea and Mauna Loa Volcanoes on the southeastern part of the Island of Hawaii (fig.
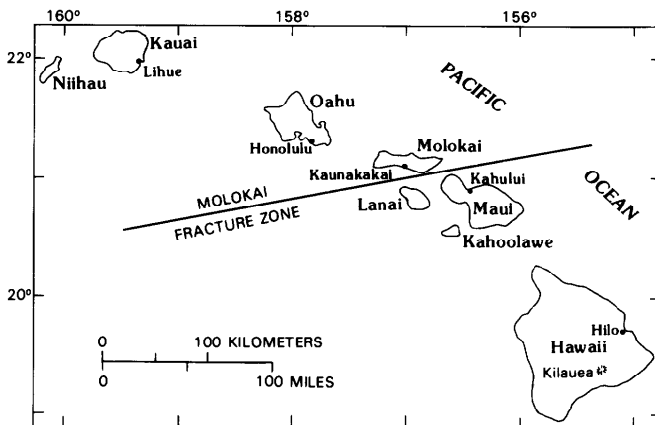
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FIGURE 22.1.—Index map of the Hawaiian Islands, showing location of the Molokai fracture zone.

22.2) are now the most active in the chain. Another volcano, Loihi, is growing on the ocean floor off the southeast coast of Hawaii (Moore and others, 1982; fig. 22.2), though it probably will not rise above the ocean surface for many thousands of years.

Hawaiian volcanoes consist largely of basaltic lava flows that were highly fluid and traveled as much as tens of kilometers from their source vents. Their cones typically are broad in comparison to their height and are called shield volcanoes. During their growth, many of these volcanoes developed elongate systems of near-vertical fractures along zones of weakness called rifts or rift zones, which lead from the volcano centers outward through their flanks. Magma moving up into a volcano rises along the central conduit, and much is erupted from vents at the summit, but some magma may spread outward into the rift zones and be erupted there. In addition, a few eruptions occur at vents on the volcanoes' flanks outside the rift zones.

Hawaiian volcanoes typically follow an evolutionary pattern. In an early stage, during which the main shield is built, eruptions of highly fluid lava are frequent and voluminous; Kilauea and Mauna Loa on the Island of Hawaii are in such a stage now. Later, eruptions become less frequent but commonly are more explosive. Hualalai and Mauna Kea on the Island of Hawaii are now in this stage and probably also Haleakala on the Island of Maui; none of these volcanoes can be regarded as extinct. Sporadic eruptions can occur on Hawaiian volcanoes for many tens of thousands of years after their shield building stage has ended.

Most eruptions that build the volcanoes are not explosive, but activity at the onset of an eruption often is vigorous enough to produce fountains of molten lava that reach tens to hundreds of meters above the vent. Large lava clots fall back and may be included in spatter ramparts or lava flows, but small particles of molten and solidified lava from the fountains are carried by wind away from the vent area and fall to produce deposits of tephra. Continued and less vigorous emission of lava produces lava streams that flow away from the vent. Lava that flows into the sea can be

explosively disrupted by steam, producing mounds of lava fragments called littoral cones along the shore.

Explosive eruptions are not as frequent as lava flows, but they have occurred repeatedly in Hawaii and produce a variety of products. Large clots of lava and solid rock fragments thrown high into the air by explosions fall back close to the vent to form cinder cones. Finer particles are carried away by wind, forming ash deposits that can be as much as a few meters thick near the cone. Explosions can also create cloudlike mixtures of rock fragments and gases, called pyroclastic surges, which typically spread from vents outward along the ground surface at high speed. Ash-laden clouds that rise above pyroclastic surges can also be carried away by winds and form beds of ash.

Volcanic gases are emitted during every kind of eruption and at many vents during intervening dormant periods. Gases generally are quickly diluted by air as they are dispersed downwind, although their odor may be detectable for many tens of kilometers.

Eruptions have been frequent in historical time, about the last 200 years. Kilauea and Mauna Loa have each erupted dozens of times during this period, and Hualalai erupted as recently as A.D. 1801 (Moore and others, chapter 20; Macdonald and Abbott, 1970). Haleakala Volcano on Maui last erupted about 1790 and
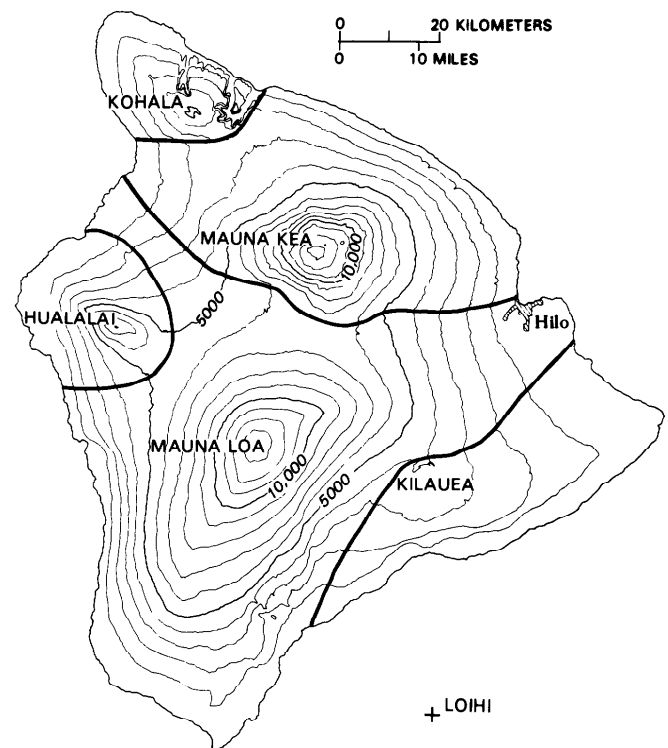

FIGURE 22.2.—Location and topography of the five volcanoes that form the Island of Hawaii, and location of the still-submerged offshore volcano Loihi. Contour interval 1,000 feet (approx. 300 m). Heavy solid lines mark boundaries of the five volcanoes.

has been active at least 10 times within the last 1,000 years (Crandell, 1983).

Several other volcanoes, though dormant during the last 200 years, are not extinct. Mauna Kea has erupted several times within the last 10,000 years (Porter, 1973) and, among those other volcanoes, has the highest eruptive probability. Other potentially active volcanic areas, such as the southeastern part of Oahu, apparently have not erupted for more than 10,000 years. The possibility of future eruptions in those areas should be recognized, even though specific preparation for such eruptions may not be economically or socially practical.

DIRECT VOLCANIC HAZARDS

Among direct volcanic hazards, lava flows occur most frequently and are the greatest hazard to property. Eruptions of tephra are also frequent but do not represent a severe hazard to people or property. Although pyroclastic surges are relatively infrequent, they can be a great danger to human life. Volcanic-gas emissions, in contrast, are common and continuous but represent relatively little danger to people or property.

LAVA FLOWS

Lava is erupted from single vents and from long fissures, and typically forms tongue-shaped to broadly lobate flows that extend downslope from the vent (fig. 22.3). The size, extent, and kind of movement of lava flows vary greatly, depending on such factors as the rate and volume of eruption and the topography over which the lava moves.

Hawaiian lava flows generally advance more slowly than the speeds at which people normally walk (3–5 km/h) but some may move much faster. Fronts of voluminous flows on steep ground have advanced as rapidly as 9 km/h, and lava streams in well-established channels on steep slopes may reach speeds of 55 km/h (Macdonald and Abbott, 1970, p. 23). Contrasting flow behavior and surface features divide most lava flows in Hawaii into two types, termed pahoehoe and aa. Pahoehoe lava is relatively fluid and forms flows that are thinner than the more viscous aa flows, and pahoehoe flows are more strongly controlled by minor topographic features. Individual pahoehoe flows range in thickness from a few tens of centimeters to as much as 3 m. During the course of a single eruption, however, successive pahoehoe flows moving along the same path may build up thicknesses of many tens of meters. Individual aa flows are generally 2–8 m thick, but locally they can be as thick as 20 m.

Hawaiian lava flows range from a few meters to more than 50 km in length, and from a meter or two to about 3 km in width. A critical factor in assessing hazards from future lava flows is the maximum distance they can be expected to extend. Although the majority of past flows from Mauna Loa have not extended more than 10–15 km from their vents, some have reached much farther in only one or a few days. The longest lava flows apparently reached their maximum extents quickly, before the loss of heat or gases caused their fluidity to decrease, or they formed lava tubes that minimized loss of
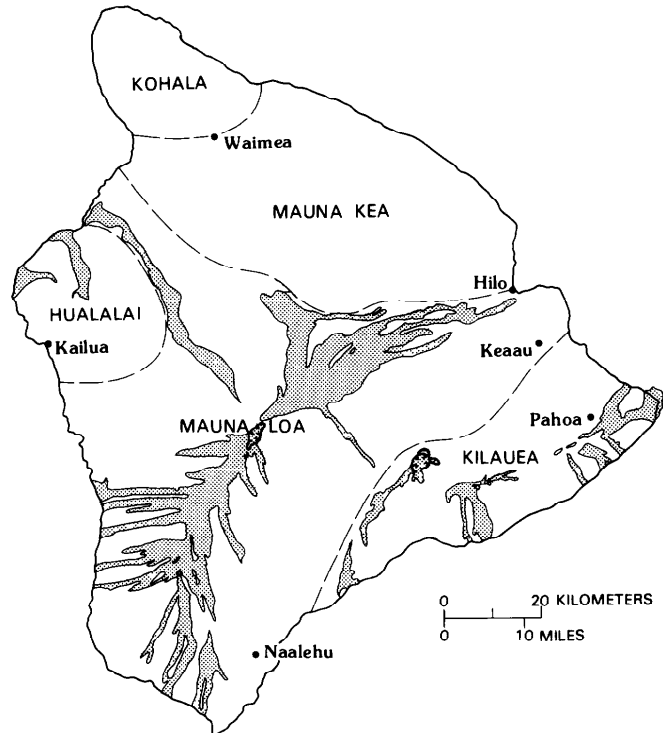

FIGURE 22.3.—The Island of Hawaii, showing approximate areas covered by pre-1975 historical and some prehistorical lava flows (stippled). Dashed lines mark the boundaries of the five volcanoes that form the island.

heat and gases. Of many factors that influence the length of lava flows, Walker (1973) proposed that rate of eruption of the lava is most important, and that it could be used to predict the distance a lava flow will travel. Malin (1980), however, pointed out that rate of lava eruption does not correlate well with length of lava flows from Kilauea or Mauna Loa; those flows correlate more closely to volume. In 1984, a lava flow from Mauna Loa extended more than 25 km toward Hilo in less than 5 days (Lipman and Banks, chapter 57). Decreases in eruption rate then triggered channel blockages and branching of the flow (Lipman and Banks, chapter 57), and the flow did not reach closer to the city. A high sustained rate of lava eruption clearly indicates that a lava flow could reach far from the vent. The most useful clues to the probable final length of such a flow may be determination of whether the rate of eruption is constant or changing, and whether or not the flow forms a lava tube.

The paths followed by lava flows are generally downslope, but they may vary in detail. Because parts of a flow are continually cooling and becoming more viscous, the flow may not move directly into the lowest available ground as would a stream of water. Lava flows may move diagonally down slopes or even cross low ridges.

The chief threat presented by lava flows is to property that cannot be removed. They burn, crush, bury, or surround structures that lie in their paths, and reduce the value of land that is covered. Although most lava flows move so slowly that they do not threaten

lives, voluminous flows, especially those on steep slopes, can move rapidly enough to endanger people.

TEPHRA FALLS

Tephra, which consists of volcanic ash and coarser fragments, is produced most frequently in Hawaii by lava fountains, but it can also be formed by explosive magmatic eruptions and by steam-blast (phreatic) explosions, both of which throw large and small fragments of molten and solid rock into the air. Large clots of lava erupted in fountains may still be molten when they fall to the ground, where they may become part of a flow or form spatter cones and ridges near the vents. Fragments ejected during eruptions that are more vigorous, and often more continuous, partly or wholly solidify before they fall back to the ground surface, and these form cinder cones around the vent. Tephra produced by steam explosions generally consists of pieces of previously solidified rock. Steam-blast eruptions such as those at Kilauea in 1924 probably resulted when ground water entered hot zones inside the volcano (Macdonald, 1972, p. 245; Decker and Christiansen, 1984). Locally, mounds of tephra (littoral cones) can be built by steam explosions where lava flows enter the ocean.

Large tephra fragments fall close to their source vents, but smaller particles commonly are carried away by winds to form widespread ash deposits. Tephra deposits are also thick near source vents, and thin rapidly with increasing distance. Tephra from lava fountains at Kilauea Iki in 1959, for example, is more than 3 m thick at 0.5 km from the vent, but thins to about 15 cm and 3 cm at distances of 2 km and 4 km, respectively (Richter and others, 1970; figs. 22.4, 22.5). Tephra from eruptions that built cinder cones on Mauna Kea is as much as a meter thick at distances of 1–2 km and 10 cm thick at about 5 km (Porter, 1973). An ash layer about 2,500 years old on the west flank of Haleakala on Maui is as much as 10 cm thick at about 9 km from the crater. Repeated eruptions of tephra from the same or nearby vents can result in even thicker deposits; widespread, prehistoric ash deposits on the Island of Hawaii are locally nearly 20 m thick (Stearns and Macdonald, 1946), and similar deposits as thick as 6 m blanket a large area on the upper northwest flank of Haleakala. Traces of ash from lava fountains commonly have been seen at distances of 40–50 km during historical eruptions of Kilauea and Mauna Loa. Tephra from steam-blast eruptions generally is coarse-grained and no more than a few tens of centimeters thick. Large fragments from the 1924 eruption at Kilauea, some weighing several tons, were thrown hundreds of meters, and smaller rocks were thrown as far as about 2 km (Jaggar, 1947; Macdonald and Abbott, 1970).

Lava fountains and eruptions that form cinder cones are spectacular but seldom endanger people or animals, who can move upwind or out of the range of the falling material. No human deaths or serious injuries from such eruptions have been reported in Hawaii during the 19th or 20th centuries. Steam-blast eruptions, however, can occur abruptly and eject large fragments that represent a distinct threat to people and animals. At least one person, in 1924, has been struck and killed by large fragments ejected in an explosive eruption

(Macdonald and Abbott, 1970).

Tephra can seriously affect vegetation and manmade structures and machinery. Property may be burned and abraded by airborne particles, damaged by impact of large fragments, or buried by a blanket of ash. Ash can also cause discomfort and even injury to eyes and respiratory systems, and can smother vegetation, clog water and sewage systems, and damage machinery.

Tephra from eruptions during historical time that is thick enough to have caused severe damage has been limited to areas less than about 2 km from active vents. Tephra deposits from eruptions of Kilauea and Mauna Loa have covered the ground to thicknesses of more than 15 cm only within about 2 km from the vents. The thickness of tephra and the damage it causes gradually decrease at progressively greater distances.

PYROCLASTIC SURGES

Some explosive eruptions produce pyroclastic surges, which are clouds of ash, rock fragments, and gases that move at high speed outward from a source vent. Although pyroclastic surges move along the ground surface, they may or may not follow topographic depressions. The temperature of rock material in some surges is higher than the boiling point of water, but in others can be lower. Pyroclastic surges are commonly caused by steam explosions or by explosions of magma and steam. These explosions can originate in at least four ways: (1) interaction between ground water and molten rock in a fluctuating magma column; (2) sudden depressurization of a shallow hydrothermal system; (3) intrusion by magma into water-saturated rocks; and (4) movement of sea water directly into a conduit during submarine eruptions. Prehistoric explosive eruptions of Kilauea have been attributed to the first two causes (Decker and Christiansen, 1984).

Explosive eruptions can produce, in their early stages, a primary surge that moves laterally away from the explosion site in all directions, as well as a vertical eruption column. Secondary pyroclastic surges can develop when material falls back to the ground from the vertical column. Although velocities of 50 km/h to as much as 300 km/h can be inferred for some surges, they decelerate rapidly and typically stop less than 10 km from their source (Crandell and others, 1984).

Pyroclastic surges formed by eruptions at basaltic volcanoes have affected areas as far as 10 km from their source vents (Crandell, 1983; Dzurisin and others, in press). The probability that an area will be affected by a surge, as well as the severity of the effects, decrease progressively away from a vent. Because surges do not necessarily follow topographic lows, high areas may not be safe. Pyroclastic surges formed by eruptions at Rotomahana-Waimangu, New Zealand, in 1886 extended at least 6 km from their source area and surmounted steep hills as high as 360 m above the vents and 200 m above the adjacent land surface (Nairn, 1979).

A series of explosive eruptions at the summit of Kilauea about 2,000 years ago produced at least three pyroclastic surges (Dzurisin and others, in press). The first two were separated by lava-fountain
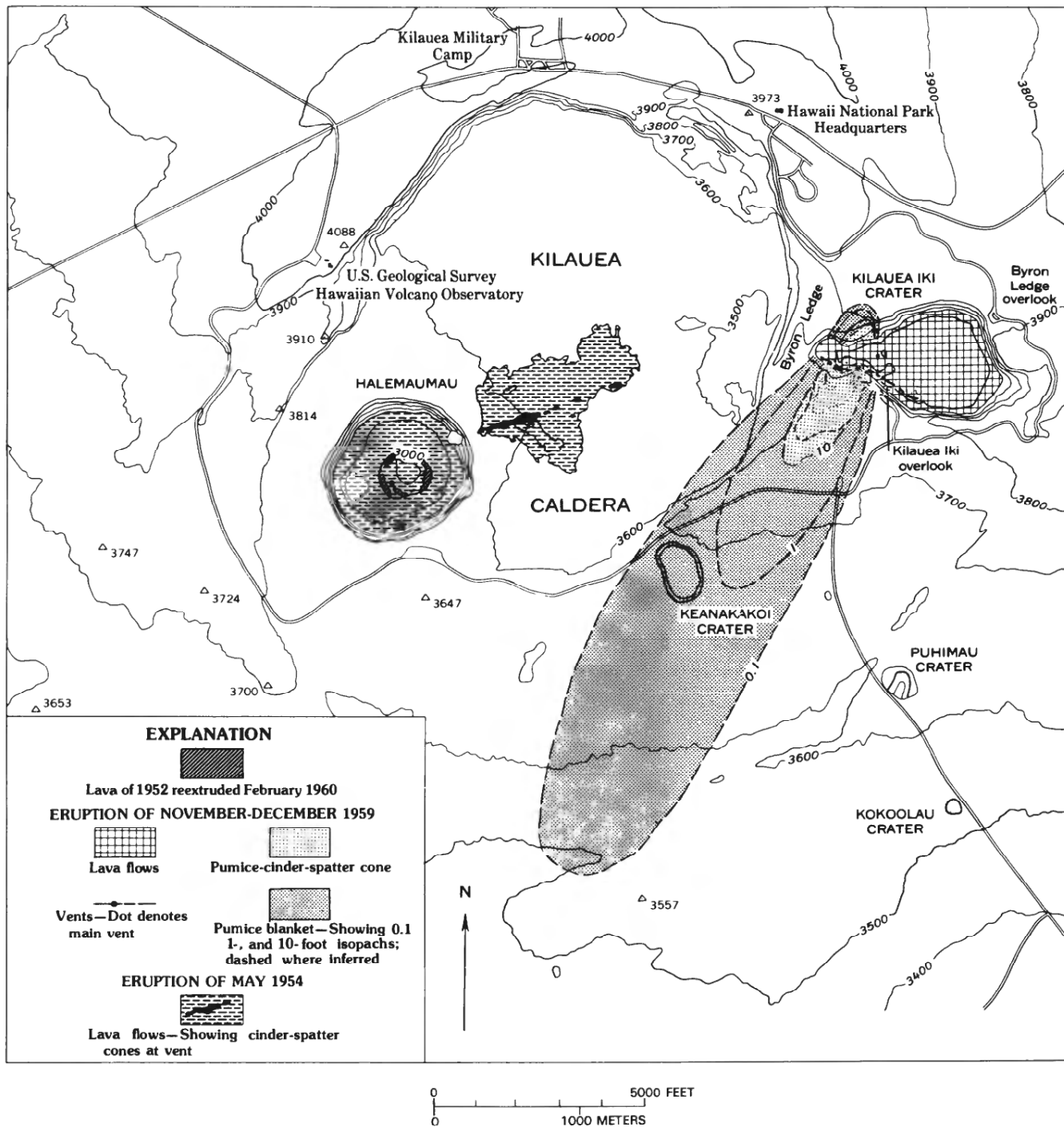
FIGURE 22.4.—The summit area of Kilauea, showing extent of tephra (pumice) blanket from Kilauea Iki vent in 1959. From Richter and others (1970). Topographic contours in feet.

eruptions, and the second and third by lava fountaining and an explosion that produced a shower of rock fragments. The last surge was followed by more fountains and by lava flows. These surges affected areas at least 10 kilometers from the vent area. Pyroclastic surges originating in the same area about 1790 left deposits of rock debris locally more than 10 m thick near Kilauea's summit caldera (Decker and Christiansen, 1984; fig. 22.6) and may have affected areas as far as 9 km from the vent. Prehistoric pyroclastic-surge

FIGURE 22.5.—Tephra (pumice) blanket in former picnic area 1 km southwest of Kilauea Iki vent, on November 30, 1959. Small shelter after 3rd phase of activity; about 1 m of tephra covers ground. From Richter and others (1970).

FIGURE 22.7.—Volcanic gases issuing from the Mauna Ulu vent on the upper east rift zone of Kilauea in about 1972. Distance across the photograph from left to right, through the vent, is about 2 km.

deposits also have been recognized at many localities on the southeastern part of Oahu, and on the islet of Molokini off the southwest coast of Maui.

Although less frequent than lava flows, explosive eruptions that produce pyroclastic surges represent a severe hazard to lives. The chief hazards to people are from asphyxiation by hot ash, impact by rock fragments traveling at high speed, and burns from hot and
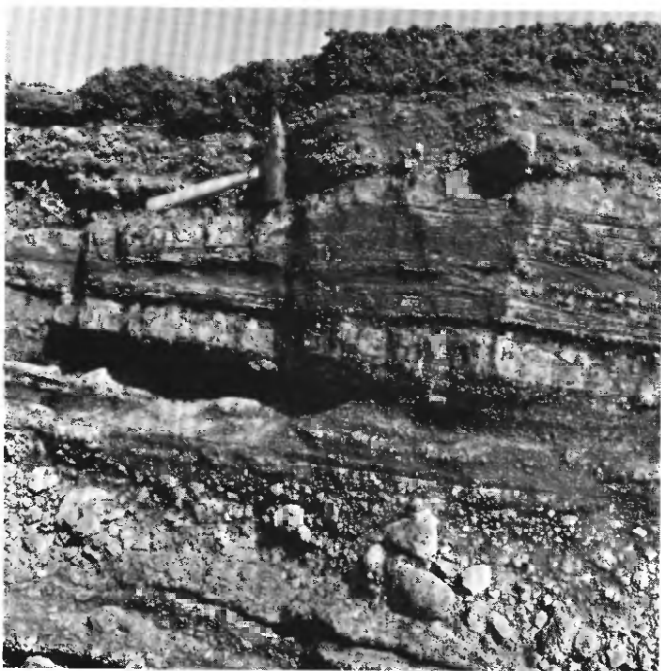

FIGURE 22.6.—Interbedded tephra-fall deposits and pyroclastic-surge deposits (with inclined bedding) that were explosively erupted from Kilauea caldera in 1790. Photograph by R.L. Christiansen, U.S. Geological Survey.

perhaps wet, clinging ash. The positions and condition of bodies of persons killed by pyroclastic surges during the 1790 eruptions of Kilauea indicated that asphyxiation and heat caused the deaths, rather than injuries resulting from impact by rock fragments (Swanson and Christiansen, 1973). The chief hazards of pyroclastic surges to property are impact and blast effects; vegetation as well as structures can also be burned, buried, and abraded.

VOLCANIC GASES

Volcanic gases are emitted during all types of eruptions (fig. 22.7) and can continue to be released for many years after other eruptive activity ceases. Gas can also be expelled at vents that have never erupted lava; some fumaroles have produced gases for more than a century. The most abundant constituents of volcanic gas in Hawaii are water vapor, sulfur dioxide, and carbon dioxide, but many other gases have been detected (Macdonald, 1972, p. 50). The gases of most concern to human health are various combinations of sulfur, oxygen, and hydrogen, such as hydrogen sulfide and sulfur dioxide; other dangerous gases include chlorine, fluorine, and carbon monoxide. Carbon dioxide can collect in closed depressions and cause asphyxiation. Small amounts of mercury have also been detected in gases emitted from vents along the east rift zone of Kilauea (Siegel and Siegel, chapter 35; Siegel and Siegel, 1978).

No deaths from volcanic gases have been reported on Hawaii, although gases have killed people elsewhere, notably in Indonesia (LeGuern and others, 1982). Brief exposure to gases generally does not harm otherwise healthy persons, but it can endanger people with heart and lung ailments. The hazard is greatest downwind from and near active vents, and it may persist at vents that continue to fume during inactive periods. Gases mix with air as they drift downwind, and their concentrations and effects diminish with increasing distance from the source. Even small concentrations of sulfur-bearing gases

can affect the lungs, eyes, and skin, and may cause gastric upsets. Furthermore, these gases can combine with water to form sulfuric acid, which can damage live tissue, cloth, metal, and other materials. Many types of vegetation cannot survive near gas-emitting vents, and many varieties may be killed as far as 30 km from the source vents. Some volcanic gases, such as carbon monoxide and carbon dioxide, are odorless and heavier than air, and during windless periods they may become concentrated in topographic depressions and present an invisible danger of asphyxiation. The presence of sulfur-bearing volcanic gases generally can be detected by their odor.

INDIRECT VOLCANIC HAZARDS

Ground fractures, subsidence, and earthquakes commonly occur together as a result of magma movement. They are especially common in the summit areas and rift zones of Kilauea and Mauna Loa but are generally not severe. These hazards also occur on a larger scale along the flanks of Kilauea and Mauna Loa as a result of massive landslides (Lipman and others, 1985), and tsunamis accompanying earthquakes may affect coastlines of the islands. Such earthquakes endanger property, and the tsunamis are a great threat to lives. Earthquakes that affect Hawaii are also caused by crustal movements underneath the volcanoes, and many tsunamis that affect the islands are generated elsewhere in the Pacific Ocean.

GROUND FRACTURES

Ground fractures in rock and soil are caused when the mass on one side shifts away from or slides past an adjacent mass along a crack. Fractures may form scarps where one mass moves up or down relative to another. Cracks as much as several meters across can remain open for long periods, and some are many kilometers in length.

Cracks can form rapidly or slowly, and by repeated discrete movements or by slow, more continuous movements. Repeated vertical displacements along the same fracture can produce a scarp as high as several hundred meters.

Most fractures in the Hawaiian Islands result from magma movement, subsidence of landslide blocks, or earthquake shaking. Fractures of historical age caused by magma movement are very abundant in summit areas and rift zones on Kilauea and Mauna Loa (fig. 22.8), and prehistoric fractures, probably of similar origin, are common along the southwest rift zone of Haleakala. The gravitational subsidence of large landslide blocks on the flanks of Kilauea and Mauna Loa also creates fractures.

Earthquakes cause fractures by ground vibration and also by triggering landslides, especially in loose soils. The earthquakes of April 26, 1973, November 29, 1975, and November 16, 1983, for example, caused cracks at many places on the Island of Hawaii.

Ground fractures are a minor but persistent hazard to people and animals. Cracks that open suddenly could trap them, and a danger would remain for as long as the cracks stayed open, especially where they are hidden by thick vegetation. Ground

FIGURE 22.8.—Subsidence of a graben in the Kapoho area on the lower east rift zone of Kilauea, on January 13, 1960, prior to outbreak of eruption in the area. View eastward along the Kapoho fault scarp in the village of Kapoho. Maximum vertical displacement is about 1 m (3.5 feet). Photography by R.T. Haugen, National Park Service.

fractures also threaten property: they can disrupt roads and buildings as well as water, sewer, power, and telephone lines.

GROUND SUBSIDENCE

Ground subsidence consists mainly of four kinds that differ greatly in scale: (1) subsidence of entire islands, (2) subsidence of parts of a volcano's flanks, (3) settling of small areas as a result of underground movement of magma, and (4) local collapse of the roofs of lava tubes.

Subsidence of some islands is slow but continuous, and the resulting submergence along shorelines is augmented by slow, worldwide rise of sea level. The rate of subsidence for the Island of Hawaii, which differs from place to place on the island, has been calculated as 1.4–4.1 mm/yr (Moore, chapter 2; Apple and Macdonald, 1966; Moore and Fornari, 1984). The worldwide rise of sea level is 1–2 mm/yr, thus the island is being submerged at approximately 3–6 mm/yr, equivalent to 1–2 feet per century. At Kahului, Maui, the rate of island subsidence may be as much as 1.7 mm/yr (Moore, chapter 2; Moore, 1970) and the overall submergence about 3 mm/yr, equivalent to 1 foot per century. Subsidence of such large areas is believed to result from depression of the sea floor under the weight of the islands. Coral reefs, beach rock, and soils encountered in drill holes on Oahu at depths as much as 336 m below sea level (Stearns, 1966, p. 21) indicate that the Island of Oahu also has subsided in the past. Tide-gauge records indicate that the island is now being submerged at the same rate as the worldwide rise in sea level, thus it apparently is stable now (Moore, chapter 2; Moore and Fornari, 1984).

FIGURE 22.9.—Stepped topography produced by subsidence of large landslide blocks on the south flank of Kilauea. The scarps are formed by repeated downward movement of blocks south of faults. Each episode of movement develops new ground cracks; such cracks are visible on face of scarp in foreground. Scarps are partly mantled with lava erupted from Mauna Ulu in 1969–74. Photograph by R.I. Tilling, U.S. Geological Survey.

Submergence from slow, continuous subsidence and sea-level rise will eventually endanger shoreline facilities. Low-lying coastal sites will become increasingly threatened by damage from storm waves and tsunamis, and eventually by inundation. Submergence is thus a factor to be considered in long-range plans for buildings and other facilities in all coastal areas of the Hawaiian Islands, and especially on the Islands of Hawaii and Maui.

Most other types of subsidence are more rapid. Large parts of the flanks of Kilauea and Mauna Loa, for example, sometimes subside abruptly. The areas affected may be several tens of kilometers long and involve hundreds of square kilometers of land (Lipman and others, 1985). Steep scarps and stair-step topography along fault zones on the flanks of both volcanoes were formed by repeated movements during the recent geologic past (fig. 22.9). These movements result from instability of the volcanoes' flanks caused in part by intrusion of magma into rift zones and in part by the load of the unbuttressed seaward flanks of the growing volcanoes (Moore and Fiske, 1969; Swanson and others, 1976).

Rapid subsidence can damage or destroy manmade structures by tilting, shaking, and fracturing the ground. It endangers areas along shorelines because they may suddenly become inundated or lowered enough to be vulnerable to damage from storm waves and tsunamis.

Shallow underground movements of magma can also cause subsidence. Withdrawal of magma from beneath summit areas and rift zones may remove support from tracts of land and cause them to subside. Such movements may be no more than a few meters, but the summation of repeated settling can amount to tens or hundreds of meters. This process produced the summit calderas and pit craters of Mauna Loa and Kilauea, which are as much as several hundred meters deep.

Subsidence caused by withdrawal of magma is restricted to summit areas and rift zones; manmade structures in those areas can be damaged or destroyed by tilting or by differential settling of underlying rock. Some depressed areas may become more vulnerable to inundation by water or lava flows. This type of subsidence is so commonly associated with eruptions and so restricted to summit and rift-zone areas that its effects are overshadowed by those caused directly by eruptions.

Collapse of roofs of lava tubes is a minor subsidence hazard. Roof collapse can occur while lava is still moving through a tube, or later, especially if new loads are added by construction or heavy equipment. This hazard can be minimized by investigating for the presence of lava tubes at construction sites and along paths to be followed by heavy construction equipment. The hazard is highest on young pahoehoe lava flows of Mauna Loa and Kilauea, but it may also exist along the southwest rift zone of Maui and on the Kalaupapa Peninsula of Molokai.

EARTHQUAKES

Thousands of earthquakes occur each year in the Hawaiian Islands; most of them originate on the Island of Hawaii and result from the movement of magma at shallow depths (see Klein and others, chapter 43). These earthquakes commonly are associated with volcanic eruptions, but they also accompany movements of magma that does not reach the surface. The greatest number of earthquakes on the Island of Hawaii originate beneath the summit areas and along or near the rift zones of Kilauea and Mauna Loa. Most are so small that they can only be detected by instruments and cause no damage, but some are strong enough to be felt, and a few cause minor to moderate damage.

Some earthquakes are less directly associated with volcanic activity, and a few of these cause major damage (Klein and others, chapter 43). Such earthquakes originate every few years under the Island of Hawaii and are less frequent beneath and between other islands of the Hawaii group. Some of these earthquakes probably originate within or at the base of the volcanoes (Lipman and others, 1985) and others in the Earth's crust beneath the volcanoes. A major zone of structural weakness, the Molokai fracture zone, extends westward from North America and intersects the Hawaiian Islands (fig. 22.1). It has been the site of occasional strong earthquakes, some of which were centered close enough to the islands to be damaging. This structural zone holds the potential for generating major, though infrequent, earthquakes in the future.

The two largest earthquakes in Hawaii, in 1868 and 1975, had magnitudes greater than 7 and probably were caused indirectly by movement of magma into rift zones of Mauna Loa and Kilauea, respectively. Magma forced the flanks of the volcanoes outward, and the earthquakes resulted from the abrupt subsidence of part of the south flank (Swanson and others, 1976; Tilling and others, 1976; Lipman and others, 1985).

Earthquakes endanger people and property directly by shaking structures and by causing ground fractures, ground settling, and landslides. Earthquakes can also be associated with tsunamis when

both result from the sudden subsidence of a volcano's flank. Strong earthquakes in the past have damaged buildings, water tanks, and bridges, and have disrupted water, sewer, and telephone lines. Locally, such damage can be intensified where soft, saturated sediments amplify earthquake ground motions. Earthquakes also trigger rockfalls and other kinds of landslides, fracture the ground, and cause confined bodies of water to slosh back and forth. Indirect effects from shaking, such as fire, can be even more severe than direct effects.

Only a few earthquakes in Hawaii have been strong enough to cause severe and widespread damage. The frequent earthquakes caused directly by magma movement do not seriously endanger life or property; most damage resulting from the strongest earthquakes of this type has been related to the falling of loose objects. The strongest historical earthquake, in 1868, was centered beneath the south coast of the Island of Hawaii (Wood, 1914). It caused widespread and locally major damage across the entire island, triggered a destructive mudflow near the community of Pahala, and was accompanied by a devastating tsunami. The combined effects of this earthquake claimed 40–50 lives. A similar earthquake in 1975 caused widespread damage, and an accompanying tsunami claimed two lives (Tilling and others, 1976).

TSUNAMIS

Tsunamis, also called seismic sea waves or tidal waves, are large, rapidly moving ocean waves. Most tsunamis are associated with earthquakes and are generated when an abrupt movement of the ocean floor displaces a large mass of water. Tsunamis also have resulted directly from volcanism and from landsliding. Tsunamis that have originated around the rim of the Pacific Ocean at great distances from Hawaii have destructive effects similar to those that originate locally, and they are discussed along with locally generated tsunamis.

Tsunamis reportedly have swept onshore to heights as great as 40 m above sea level at some localities in the world, but the maximum recorded height reached by such a wave anywhere in Hawaii has been 16–17 m (Tilling and others, 1976). The heights and distances inland reached by different tsunamis, and on different coasts by the same tsunami, however, have varied greatly. The tsunami of November 29, 1975, reached as high as 14.6 m on the south coast of the Island of Hawaii (Tilling and others, 1976), but waves were only 1–2.4 m high on other parts of that island and less than 1 m high on the other islands. Recently, Moore and Moore (1984) have suggested that coral-bearing gravel deposits on some of the islands, formerly interpreted as beaches formed during high stands of sea level, are actually the result of a truly giant wave possibly generated by a submarine landslide.

Although the effects of tsunamis that originate at great distances are similar to those generated locally, the latter are potentially more dangerous because the time between their origin and arrival at the shoreline may be too brief to warn and evacuate people or property.

Tsunamis sometimes move onshore as turbulent waves that can damage or destroy virtually everything in their paths. People may be battered or drowned, buildings moved off their foundations or knocked over, trees uprooted, and boats carried inland. As the waves recede, they may carry people and property out to sea. Tsunamis can also rise quietly as they move onshore and inundate nearshore areas. The salt water can kill crops, poison soil, corrode metal, and damage objects and structures in other ways. The actual effects of a tsunami at any specific site will be determined by the details of local topography, both offshore and onshore, and the direction of approach of the wave, and they are difficult to predict.

The locally generated tsunami of April 2, 1868, destroyed most villages along the south coast of the Island of Hawaii and killed an estimated 46 people (Brigham, 1909, p. 495–496; Hitchcock, 1909; Wood, 1914). Five successive tsunamis that accompanied the earthquake of November 29, 1975, caused the loss of two lives and about $1.4 million in property damage.

Tsunamis have been reported in Hawaii about 50 times since the early 19th century (Macdonald and others, 1947). Those of 1837, 1868, 1877, 1946, 1960, and 1975 caused major damage. The tsunaumi of 1946 originated in Alaska and reached the islands without warning; it caused 150 deaths and $25 million damage (Macdonald and others, 1947; Shepard and others, 1950). Although adequate warnings accompanied the 1960 tsunami, which originated in Chile, they were not fully heeded, and the toll included 61 deaths as well as millions of dollars of property damage (Eaton and others, 1961).

HAZARD ZONES

Volcanic-hazard zonation maps have been prepared only for the Islands of Hawaii and Maui. Volcanic eruptions on the other islands are so unlikely in the near future that similar hazard zonation is not warranted. Likewise, no hazard-zone maps have been drawn for earthquakes or tsunamis. The threat from earthquakes is widespread across the islands, and earthquake effects are strongly influenced by local conditions. The danger from tsunamis exists only along the coasts of the islands in a narrow zone whose width depends on local topographic conditions. The danger from large tsunamis is somewhat greater along the southeast and southwest coastlines of the Island of Hawaii, because highly destructive tsunamis are occasionally generated there by large landslides.

The hazard-zone maps distinguish areas in which the general level of hazard is different from that of adjacent areas. However, the level of hazard can vary considerably within any hazard zone, either gradually or abruptly. Direct volcanic hazards, for example, decrease in magnitude gradually across zones away from active vents. For such hazards as lava flows, the frequency with which a specific site is affected decreases with increasing distance; for other hazards such as tephra and gases, the severity of effects diminishes gradually with increasing distance. Such gradational changes in the hazard may extend across an entire zone. Abrupt changes in magnitude of hazard within a zone commonly occur along sharp topographic features, and local topographic features in a zone may have a magnitude of hazard very different from that of the zone as

whole. The hills behind Ninole, for example, stand well above the adjacent slopes of modern Mauna Loa and so have a much lower lava-flow hazard than do those slopes. Consequently, the magnitude of hazard assigned to a zone applies only to that zone as a whole, and differences within it are not shown. Such differences can best be determined by specific site studies.

The change in degree of hazard across most zone boundaries is gradual rather than abrupt, and it may be apparent only over a distance of a few kilometers or more. Boundaries between many zones are approximations that serve chiefly as guidelines to show that a difference in hazard does exist and to facilitate description of the zones. Although adjacent hazard zones are separated on the maps by single lines, changes in the degree of hazard across most zone boundaries are so gradational that they might better be shown by numerous lines or a continuous change in shading.

Some zones that theoretically exist are not shown on the hazard maps. For example, in an area south of Kilauea caldera, the distribution of lava flows indicates that the hazard from future flows is much less than on the nearby southeast flank of the volcano. Zones intermediate between the two hazard zones that are shown must exist, but these intermediate zones are not drawn on the map because multiple narrow zones would suggest greater accuracy than is warranted.

Hazard zones are based chiefly on the assumption that future eruptions will be like those in the past that are known from oral and written histories and from geologic investigations. Some kinds and scales of eruptive events could occur that are not foreseen by these hazards assessments.

ISLAND OF HAWAII

HAZARD ZONES FOR LAVA FLOWS

Hazard zones for lava flows are based chiefly on lava-flow coverage of different areas during specific time periods. The zones are also based partly on the current structural conditions within the volcanoes, on fault scarps and other topographic features that would limit the distribution of lava flows, and on the frequency of past eruptive events. Recent studies of Kilauea by Holcomb (chapter 12), Mauna Loa by Lockwood and Lipman (chapter 18), and Hualalai by Moore and others (chapter 20) provide most of the data on lava-flow coverage for the time periods on which hazard zones are based. Similar data for Mauna Kea are from Porter (1973). Hazard zones and definitions used for the Island of Hawaii in this report are modified from those used for a previous volcanic-hazards assessment of the island (Mullineaux and Peterson, 1974; U.S. Geological Survey, 1976).

To facilitate comparison of the hazard from place to place across the Island of Hawaii, lava-flow hazard zones for its five volcanoes have been fit into a single scale of decreasing hazard. The overlap of hazard zones shown for Kilauea and Mauna Loa is

approximate, in part because both volcanoes have changed their eruptive patterns within the past several hundred years, and their future patterns are only partly predictable. Between A.D. 1200 and A.D. 1800, for example, Kilauea erupted voluminous lava flows from precaldera summit vents; the flows covered more than 80 percent of the volcano, including its northeast and northwest flanks (Holcomb, chapter 12, fig. 12.42). Since 1800, lava has covered significant areas of its flanks only south of its east rift zone. In contrast, lava flows on Mauna Loa since about A.D. 1840 have covered more area than those of the previous several hundred years (Lipman, 1980). Neither volcano shows signs of changing its current pattern. The hazard zones shown on fig. 22.10 are based on the assumption that present kinds and rates of activity at both volcanoes will continue unchanged for at least the next few years and probably for the next few decades.

Zone 1 (fig. 22.10) consists of the summit areas and active parts of the rift zones of Kilauea and Mauna Loa; in those areas, 25 percent or more of the land surface has been covered by lava within historical time, during the 19th and 20th centuries. These areas contain the sites of most historical eruptions, and a large majority of the lava flows that will affect other zones on Kilauea and Mauna Loa in the near future probably will originate in zone 1.

Zone 2 consists of several areas that are adjacent to and downslope from the active rift zones of Kilauea and Mauna Loa and therefore are subject to burial by lava flows of even small volume erupted in those rift zones. On Kilauea south of its east rift zone, as much as 25 percent of the land surface has been covered by lava during historical time, and 10–15 percent has been covered since 1950. Lava flows have covered parts of this area as recently as January 1986, and the history of Kilauea suggests that they will continue until some significant change occurs within the volcano. Although very little of the area in zone 2 north of the lower east rift zone of Kilauea has been affected by lava since 1950, about 15 percent of that surface has been covered during historical time. On Mauna Loa, long and voluminous lava flows have repeatedly entered the areas included in zone 2, covering about 5 percent of those areas since 1950 and about 20 percent within historical time.

Zone 3 includes other areas on Kilauea and Mauna Loa in which the hazard is gradationally lower than that in zone 2. On Kilauea, less than 5 percent of the areas in zone 3 has been covered with lava during historical time. However, more than 75 percent of those areas has been covered by lava flows within the last 750 years. The hazard is less in zone 3 on the flanks of Kilauea than in zone 2 because ground subsidence within much of Kilauea's rift zones prevents lava flows of small volume from extending beyond those rift zones. On Mauna Loa, only about 1-3 percent of the land surface in most of zone 3 has been covered by lava during historical time; however, a single lava flow during the 19th century covered about 10 percent of the area in zone 3 on the northwest flank of the volcano. During the last 750 years, lava flows have covered about 15-20 percent of the flanks of Mauna Loa within zone 3. The hazard on Mauna Loa decreases progressively downslope from its summit and

KOHALA
9
x

Waimea

8

MAUNA
KEA
x
7

8

Hilo

HUALALAI
x
4

Kailua

3

2

Keaau

Keauhou

3

3

Captain Cook

Pahoa

MAUNA LOA

2

6

3

KILAUEA

2

2

1

5

2

1

3

Punaluu

3

3

0   10   20 KILOMETERS
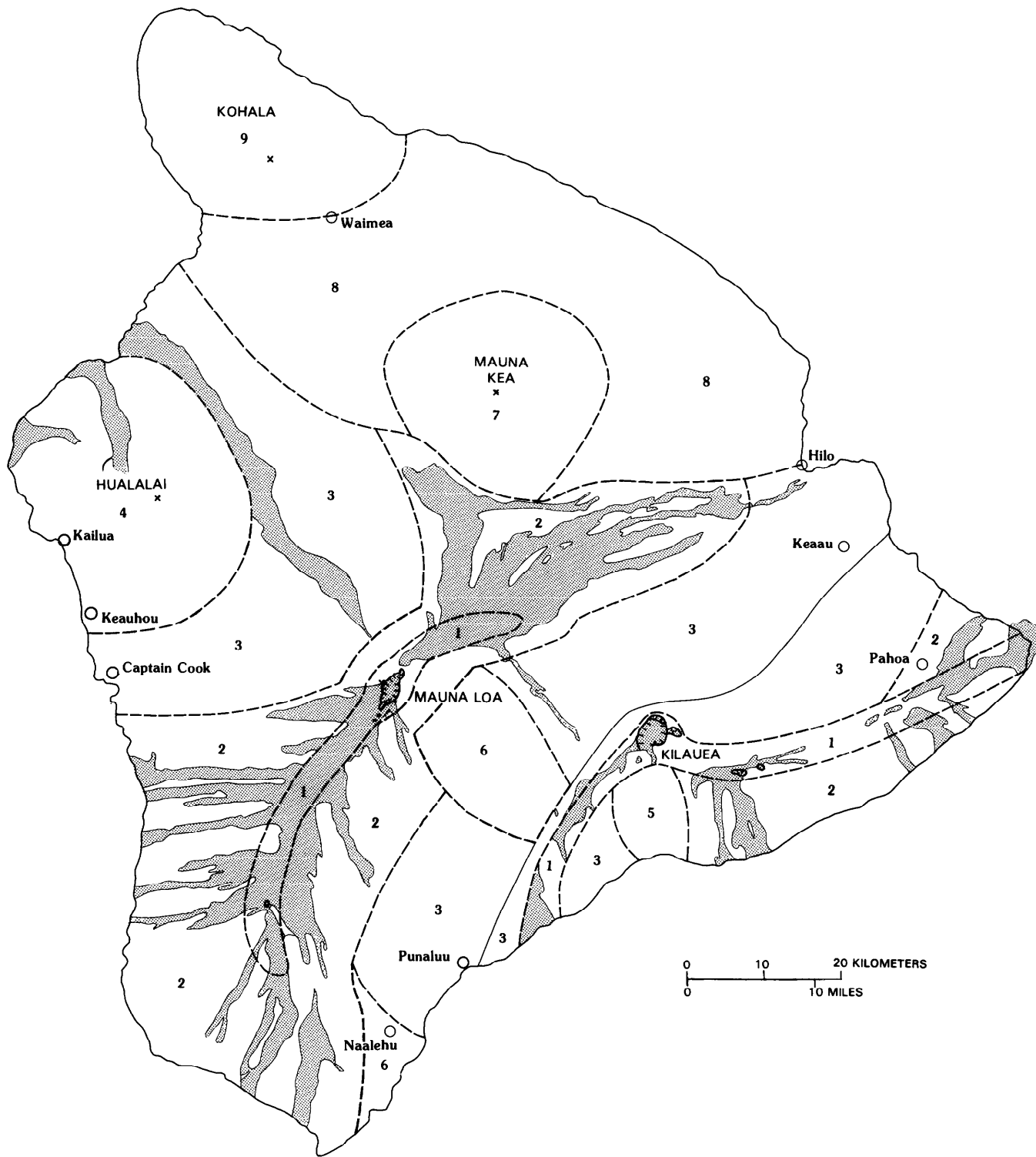0   10 MILES

Naalehu
6

FIGURE 22.10.—Hazard zones for lava flows on the Island of Hawaii. See text for explanation of numbered zones. Thin, solid line marks boundary between Mauna Loa and Kilauea Volcanoes. Stipple pattern indicates areas covered by pre-1975 historical lava flows.

rift zones across zones 2 and 3. The hazard is lower in zone 3 because lava flows on Mauna Loa typically do not extend all the way from the source vents to the coastline; only about half of the flows on this volcano during the last 1,500 years have reached its lower flanks (Lockwood and Lipman, chapter 18). Within zone 3 on Mauna Loa, the hazard is currently less in the part that lies southeast of the rift zones than on the northwest flank of the volcano and should remain so in the near future. The hills behind Ninole, east of the southwest rift zone, are not identified on the hazard-zone map. They may be an upthrown block of Mauna Loa or part of an older volcano (Lipman, 1980), and they stand as much as a hundred meters above the younger surface of Mauna Loa. The lava-flow hazard on these hills decreases with height and is about as low as that in zone 8 at their highest points.

Zone 4 embraces only Haulalai Volcano, where a few percent of the land surface was covered by lava flows in A.D. 1800-1801, but less than 15 percent has been covered during the last 750 years. Recent prehistoric as well as historical eruptions on Haulalai have been less frequent than on Kilauea and Mauna Loa. Lava flows on Hualalai have typically covered large areas, and the rift zones of the volcano do not seem to have a distinctly higher degree of hazard than do its flanks.

Zone 5, on the lower flank of Kilauea south of its caldera, has been almost unaffected by lava flows during historical time, although nearly half of this area has been covered within the last 750 years. This flank of Kilauea is currently protected by the presence of the Kilauea summit caldera and by fault scarps in the Koae fault zone that face upslope. Zone 5 seems to be relatively safe from lava-flow burial under present conditions, but it could be threatened by a new episode of voluminous eruption of lava that spilled southward from the summit caldera.

Zone 6 includes one area on the flank of Mauna Loa south-southeast of its caldera and another that is east of the lower part of its southwest rift zone. The age and extent of flows in these areas are not well known, but the oldest flows at the surface of Mauna Loa are on this flank (Lipman, 1980). These areas seem relatively unlikely to be affected by lava flows in the near future. The magnitude of the hazard south-southeast of the summit could change significantly, however, if the caldera of Mauna Loa were to fill with lava.

Zone 7 includes the summit and upper flanks of Mauna Kea; this is an area in which no eruptions have occurred since about 3,500 years ago, but lava covered about 20 percent of the land surface between 5,000 and 3,500 years ago.

Zone 8 is a large area on the lower flanks of Mauna Kea that has not been affected by lava flows for at least 10,000 years. However, zone 8 could be affected by an unusually long lava flow issuing from a vent higher on Mauna Kea.

Zone 9 consists of Kohala Volcano. No eruption has occurred there for about 60,000 years, but even though the hazard there is extremely low the volcano cannot be regarded as extinct.

HAZARD ZONES FOR TEPHRA FALLS

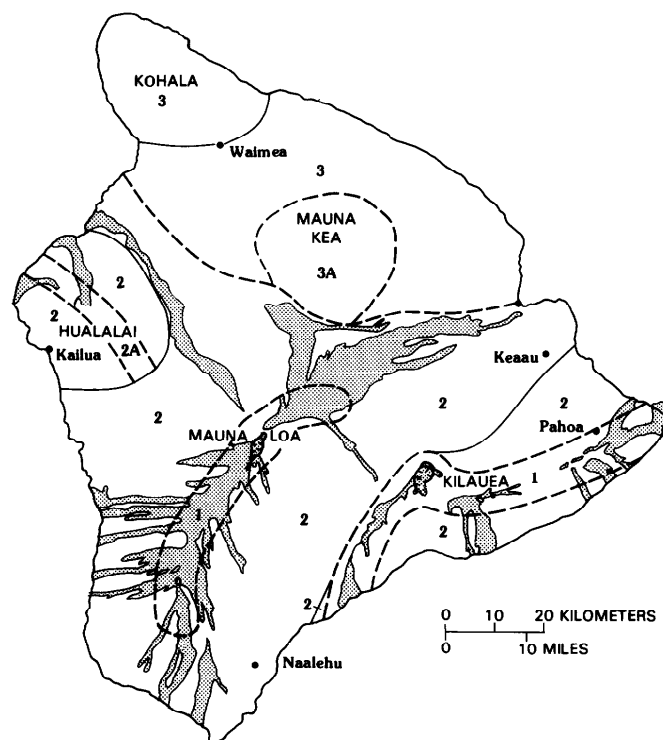Hazard zones for tephra (fig. 22.11) are based on eruption

FIGURE 22.11.—Hazard zones for tephra on the Island of Hawaii. See text for explanation of numbered zones. Thin, solid lines mark boundaries between volcanoes. Stipple pattern indicates areas covered by pre-1975 historical lava flows.

frequency, proximity to potential vents, and wind directions. Frequency and proximity largely control the location of tephra hazard zones on the Island of Hawaii, because the potential hazard diminishes rapidly in severity with increasing distance from vents as both fragment size and thickness of deposits decrease. Winds have less influence on the distribution of these hazard zones because the prevailing northeasterly trade winds are not dominant over the entire Island of Hawaii; antitrade and storm winds, especially at the altitudes of vents high on Mauna Loa, and upslope and downslope winds as well as sea and land breezes result in great variations from trade-wind directions. However, antitrade winds seldom blow from Kilauea, Mauna Loa, or Hualalai across Mauna Kea or Kohala, and storm winds blowing in those directions are infrequent.

Tephra is produced most frequently by lava fountains in the summit areas and rift zones of Kilauea and Mauna Loa. Such eruptions have occurred at least once every few years in historical time, and they have produced tephra as much as 1 m thick at a distance of 1 km from the vents and 10 cm thick at about 2 km (Richter and others, 1970). Steam-blast explosions have occurred at the summits of Kilauea and Mauna Loa and where the east rift zone of Kilauea intersects the shoreline. Tephra-fall deposits from steam-blast eruptions have included large rock fragments, but such eruptions rarely produce layers more than about 1 cm thick at localities

more than about 2 km from the source vents. Outside those zones, a few historical eruptions on the upper north slope of Mauna Loa suggest that tephra could be produced there by future lava fountains. Tephra mounds (littoral cones) can also be formed wherever lava flows enter the ocean; thus, they are limited to the seacoast, mostly on Kilauea and Mauna Loa. The hazard from tephra of this origin is not identified on a hazard map, inasmuch as it accompanies and is inseparable from the lava-flow hazard along the shoreline.

Tephra eruptions have been much less frequent on Hualalai; none are known in historical time. Such eruptions have been even less frequent on Mauna Kea and Kohala. The youngest eruptions on Mauna Kea occurred more than 3,500 years ago, but they produced tephra layers as thick as 5 m about 1 km from the source vents, 1 m at 2 km, and 10 cm at 4 km (Porter, 1973). No eruptions have occurred on Kohala for several tens of thousands of years.

Tephra-hazard zone 1 includes the summit areas and rift zones of Kilauea and Mauna Loa, the areas of highest eruption frequency, and extends about 2 km beyond the rift-zone boundaries. Tephra more than 10 cm thick, as well as large fragments, will likely be restricted to this zone during virtually all future eruptions from the summits and rift zones of Kilauea and Mauna Kea.

Tephra-hazard zone 2, in which tephra falls from lava fountains should be frequent but thin, includes the flanks of Kilauea and Mauna Loa and all of Hualalai. The potential hazard within this zone is locally somewhat greater on the upper north flank of Mauna Loa, where there are several vents along minor fractures. A subzone, 2A, of somewhat different character exists on Hualalai. In addition to the hazard there represented by thin tephra erupted from within zone 1, a potential exists for burial by cinder cones and thinner, more widespread tephra 10 cm or more thick from infrequent eruptions of Hualalai. This subzone includes the rift zone on Hualalai and the areas within about 4 km on both sides of the rift zone.

Tephra hazard zone 3 includes areas in which only thin deposits of tephra erupted from Kilauea, Mauna Loa, or Hualalai are likely to fall. The low frequency of winds that blow northward across Mauna Kea and Kohala from the three more active volcanoes indicates that even thin ash is likely from only a minority of eruptions. The subzone 3A marks an area of Mauna Kea above about a 2,000-m elevation in which cinder-cone eruptions could produce locally thick tephra deposits; although such eruptions have a very low probability, their effects could be locally severe.

HAZARD ZONES FOR PYROCLASTIC SURGES

On the Island of Hawaii, the deposits of pyroclastic surges have been recognized only adjacent to the caldera of Kilauea. The single hazard zone for pyroclastic surges surrounds the caldera and extends to a distance of 10 km from its center.

Pyroclastic surges conceivably could be initiated at other places where ground water or sea water can interact with magma. Magma could encounter ground water under the rift zones of Kilauea and the summit and rift zones of Mauna Loa and possibly at scattered sites elsewhere on Mauna Loa and on Hualalai. Magma and sea water

could interact where both rift zones of Kilauea and the southwest rift zone of Mauna Loa meet the coastline.

HAZARD ZONES FOR VOLCANIC GASES

Hazard zones for volcanic gases are the same as hazard zones for tephra (fig. 22.11); like tephra, gases are emitted chiefly from the summit areas and rift zones of Kilauea and Mauna Loa; they are distributed by winds and their effects decrease with distance. Hazard zone 1 consists of the summit areas and rift zones of Kilauea and Mauna Loa, and extends about 2 km beyond the rift-zone boundaries.

Hazard zone 2 for gases includes Hualalai as well as the other parts of Kilauea and Mauna Loa. Although the hazard is less in zone 2, historical events show that gas effects can be significant far beyond the source vents. In 1977, gases from eruptions on Kilauea killed vegetation as far as 30 km from their source (J.P. Lockwood, written commun., 1978). From 1967 to 1974, trade winds carried gases from Kilauea's summit and east rift zone southwestward into the Kau District, reportedly causing a decline in sugar yields. Fumes then drifted around to the Kona District on the west coast and were blamed for the decline of other crops.
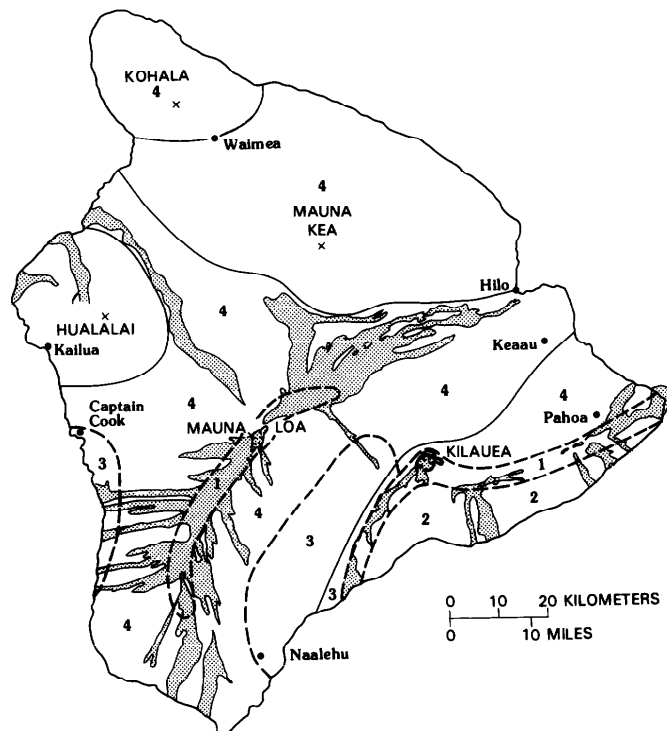

FIGURE 22.12.—Hazard zones for ground fractures and subsidence on the Island of Hawaii. See text for explanation of numbered zones. Location of areas subject to fracture and subsidence on flanks of Mauna Loa from Lipman (1980). Thin, solid lines mark boundaries between volcanoes. Stipple pattern indicates areas covered by pre-1975 historical lava flows.

Hazard zone 3 covers Mauna Kea and Kohala, which are subject to a lower degree of hazard because of their distance from vent areas and the infrequency of winds that blow across them from the south.

HAZARD ZONES FOR GROUND FRACTURES AND SUBSIDENCE

The Island of Hawaii is divided into four hazard zones for ground fracture and small-scale subsidence (fig. 22.12). The zone of highest hazard, zone 1, includes the summit areas and rift zones of Mauna Loa and Kilauea, where fractures and subsidence occur most frequently. Zone 2 consists of the south flank of Kilauea, where fracturing and subsidence occur somewhat less frequently than in the summit and rift zone areas. Fracturing and subsidence of the south flank occur chiefly along the Koae and Hilina fault zones but are not limited to them (Holcomb, chapter 12; Duffield, 1975; Lipman and others, 1985.

Hazard zone 3 embraces the areas of the Kaoiki and Kealakekua fault systems on Mauna Loa, where fractures and subsidence caused by magma movement are less frequent than on Kilauea. Zone 4, in which these hazards are least, includes the remainder of the island.

Abrupt large-scale subsidence of fault blocks causes an additional hazard from inundation along the coast seaward of the Kaoiki and Kealakekua fault systems on the flanks of Kilauea and Mauna Loa. Subsidence-induced tsunamis, however, can be a more serious hazard than the abrupt inundation. In addition, inundation hazard from slow regional subsidence exists along the entire shoreline of the island.

MAUI

The Island of Maui comprises two volcanoes, West Maui and Haleakala (Stearns and Macdonald, 1942; fig. 22.13). Potassium-
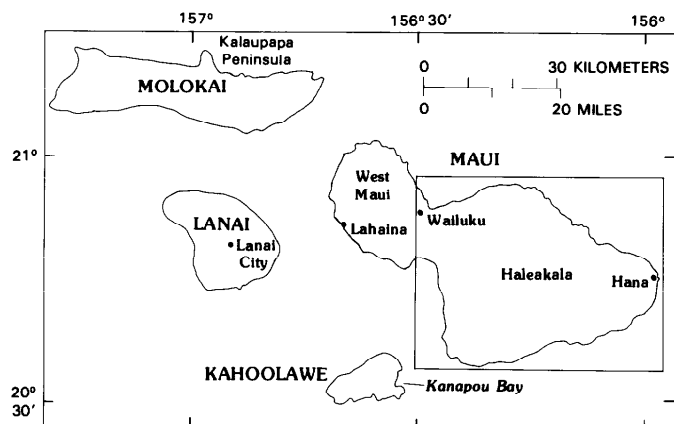

FIGURE 22.13.—The Islands of Maui, Molokai, Lanai, and Kahoolawe. Rectangle indicates area on Maui shown in figures 22.14 and 22.16.

argon ages of lavas of the West Maui volcano range from about 1.97 to 1.3 million years before present (McDougall, 1964; Naughton and others, 1980), and Crandell (1983) concluded that even the youngest lava flows on the volcano are more than 25,000 years old. The likelihood of a future eruption on West Maui seems remote.

Potassium-argon ages on lava flows of Haleakala volcano range from about 0.91 to 0.36 million years before present (McDougall, 1964; Naughton and others, 1980). Radiocarbon ages ranging from about 26,800 to 200 years before present have been reported on more recent ash deposits and lava flows (Crandell, 1983). Crandell inferred that the average frequency of eruptions on the volcano as a whole has been nearly one per 100 years during the last 1,000 years. The latest eruption occurred about 1790 at a vent in the lower part of the southwest rift zone, and it produced a 3-km-long lava flow.

HAZARD ZONES FOR LAVA FLOWS

Five zones of differing lava-flow hazard proposed by Crandell (1983) on Haleakala were based on the inferred frequency of eruptions and the ages of recent lava flows. The geologically recent eruptive history of Haleakala differs in many respects from that of the volcanoes on the Island of Hawaii. Because of these differences, lava-flow hazard zones recognized on Haleakala do not correspond exactly to hazard zones on Hawaii, and they are defined here from highest (1) to lowest (5) degree of hazard. The zones described here are the same as those outlined on a previous lava-flow hazard map of Haleakala (Crandell, 1983), but the definitions of some zones have been modified.

On Maui, lava-flow hazard zone 1 includes areas in which about 50 percent of the land surface has been covered by lava flows during the last 1,000 years, and it covers the crater of Haleakala and the southwest rift zone (fig. 22.14). The inferred frequency of lava flows has been at least one per 120 years in the crater during the last 2,500 years, and at least one per 150–200 years in the southwest rift zone during the last 1,000 years.

Zone 2 includes two areas in which 10–30 percent of the land surface has been covered by lava flows during the last 1,000 years. These areas are situated south of the southwest rift zone, where about 10 percent of the surface has been covered during the last 1,000 years, and north of the east rift zone, where lava flows have covered about 30 percent of the land surface during the same period. Lava flows are inferred to have occurred within these areas at an average rate of at least one per 500 years, and the last flow occurred less than 1,000 years ago.

Zone 3 includes areas in which eruptions have not occurred for more than 1,000 years, but where much of the land surface has been covered by lava flows within the last 20,000 years. The best evidence of rate of coverage in this zone on Haleakala is north of the southwest rift zone, where lava flows inferred to be less than 20,000 years old have covered about 75 percent of the land surface. Flows have occurred at an average rate of at least one per 2,000 years in this area, although the last flow was erupted about 4,000 years ago. The valleys that extend from the crater northward and southward to
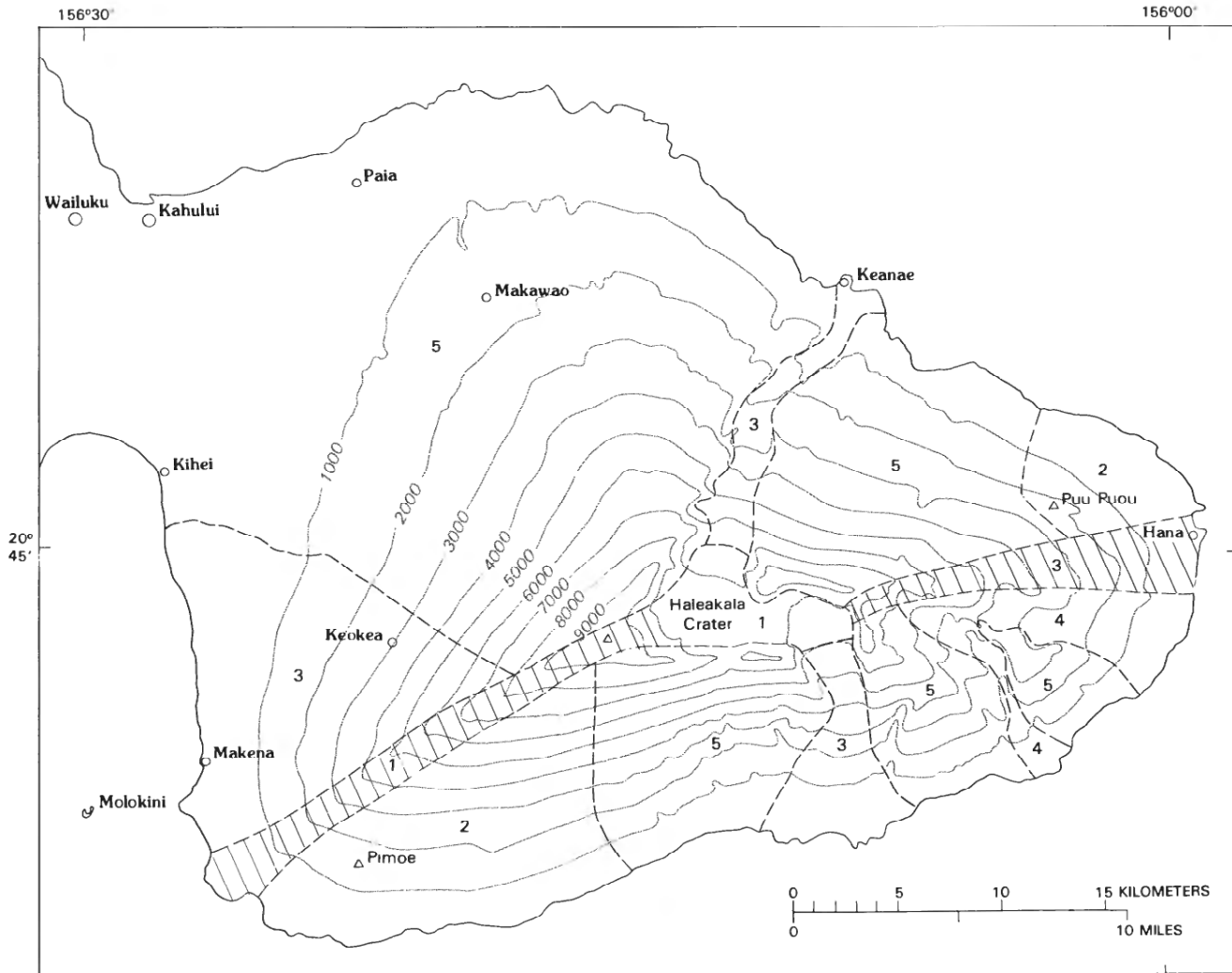
FIGURE 22.14.—Lava-flow hazard zones on Haleakala Volcano, eastern Maui. See text for description of the numbered zones. Lined areas indicate the southwest and east rift zones of the volcano. Topographic contours at 1,000-ft intervals.

the coasts, as well as the east rift zone, are included in zone 3. The two youngest flows recognized in the lower part of the southern valley were tentatively assigned an age of more than 1,000 but less than 10,000 years by Crandell (1983). A flow in the upper part of the east rift zone is radiocarbon dated at about 9,400 years before present, and one in the lower part of the rift zone is dated at 12,760 years before present. The rate of lava flow eruptions along the east rift zone probably is less than one per 2,000 years.

Zone 4 is defined solely from the average frequency of lava flows, which is inferred to be less than one per 10,000 years, but is at least one per 20,000 years. The last lava flows in these areas probably were formed more than 10,000 years ago. The rate of lava coverage is not known, but probably less than 10 percent of the area has been covered in the last 20,000 years.

Zone 5 includes areas that have not been affected by lava flows for at least 20,000 years.

Lava-flow hazard zones on Maui are compared with those on the Island of Hawaii in table 1, but the frequency of eruptions or the percentage of lava-flow cover during a specified period on one island may correspond only approximately with similar data on the other island.

TABLE 22.1.—Comparison of lava-flow hazard zones on the Islands of Maui and Hawaii

[N.R., not represented]

Lava-flow hazard zone on Hawaii	Lava-flow hazard zone on Maui
1	N.R.
2	N.R.
3	1 (?)
4	2
5	N.R.
6	N.R.
7	3
8	4
9	5

FIGURE 22.15.—View southeastward across lava flows (foreground) and cinder cones in the crater of Haleakala Volcano, eastern Maui. Cone at right side of photograph is about 150 m (500 feet) high. Average rate of eruptions in the crater during the last 2,500 years may be at least one per 100 years, but the age of the last eruption is not known.
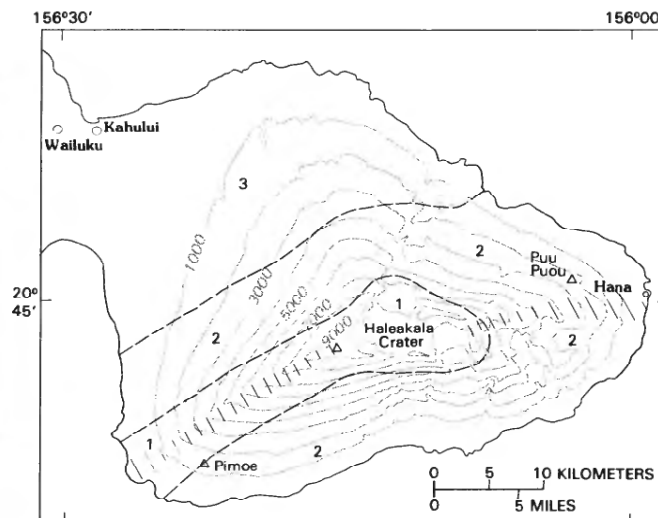

FIGURE 22.16.—Ashfall-hazard zones on Haleakala Volcano, eastern Maui. See text for description of the three zones. Lined areas indicate the southwest and east rift zones of the volcano. Topographic contours at 1,000-ft intervals.

HAZARD ZONES FOR TEPHRA FALLS

Because of the low frequency of eruptions on Maui in comparison with the Island of Hawaii, the likelihood of areas being affected by ashfall is much lower. If an ash-producing eruption does occur, the active vent probably will be within the crater (fig. 22.15) or somewhere along the southwest rift zone. Such an eruption might also occur at a flank vent, such as that represented by the Pimoe cone on the southwest side of Haleakala. Cindery ash on the northeast flank of Haleakala, northwest of Hana, probably came from a vent at or near Puu Puou (fig. 22.16). This ash is older than a 500-year-old lava flow and may be several thousand years old.

Three zones of different ashfall hazard on Maui (fig. 22.16) are based on the estimated frequency and range of thickness of future ashfalls. Within each ashfall-hazard zone, maximum thicknesses should be expected near the source vent, with rapidly decreasing thicknesses at increasing distance downwind. Zone 1 includes areas that could be affected at a rate of one ashfall per 200–500 years with thicknesss of 1–100 cm. Zone 2 includes areas in which 1–100 cm of ash could fall less often than once per 500 years but more often than once per 1,000 years and in which less than 1 cm of ash is expected once per 200–500 years. Zone 3 includes areas in which less than 1 cm of ash is expected to fall at an average rate of once per 1,000 years. This zone also includes areas in which 10 cm or more of ash may fall at least once per 3,000 years.

OTHER VOLCANIC HAZARDS

Hazard zones are not designated on Maui for pyroclastic surges, volcanic gases, ground fracture and subsidence, or earthquakes, but a few general statements can be made.

For the purpose of pyroclastic-surge hazard assessment, vents near or beneath sea level, and those in areas of high ground-water table, are regarded as areas of potential hazard from pyroclastic surges during eruptions. The most likely locations of such vents are near the coastline along the two rift zones of Haleakala. In addition, eruptions elsewhere on the windward, relatively wet, northeast side of Haleakala are more likely to be accompanied by explosions and pyroclastic surges than are eruptions at vents on drier parts of the island. The deposits of pyroclastic surges are present on the islet of Molokini, but have not been recognized on Maui.

The area of greatest potential danger to human health from volcanic gases probably is within the crater of Haleakala, because the crater is a natural basin in which heavier-than-air gases may be trapped. The crater floor would be a zone of relatively high gas hazard during an eruption. Gases erupted within the crater could also be carried by tradewinds toward the southwest and west slopes of the volcano.

Most future destructive earthquakes on Maui probably will be generated along the Molokai fracture zone (fig. 22.1) and thus could affect all or most parts of the island. For example, the earthquake of 1938, which had an epicenter about 40 km north of the island, damaged roads and structures on both Maui and Molokai (Macdonald and Abbott, 1970, p. 252; Furumoto and others, 1973).

The most likely area of ground fracture and subsidence in the future coincides with the crater and southwest rift zone of Haleakala, and these events would most likely be associated with an eruption. In addition, regional subsidence of possibly 1.7 mm/yr is occurring on Maui (Moore, chapter 2; Moore and Fornari, 1984), but this directly creates a hazard only along a narrow shoreline zone.

VOLCANIC HAZARDS ON THE OTHER ISLANDS

On islands other than Hawaii and Maui, the likelihood of an

eruption in the foreseeable future is so low that no preparation seems warranted unless premonitory signs indicate an approaching eruption. Each of these other islands is briefly discussed in the following sections.

KAHOOLAWE

The uninhabited Island of Kahoolawe is a single shield volcano with an erosionally breached caldera at its east end (Stearns, 1940; fig. 22.13). Deep weathering of rocks at the ground surface across the island (Macdonald and Abbott, 1970) and a potassium-argon age (Naughton and others, 1980) both indicate that Kahoolawe lava flows are one million or more years old. The most recent activity on the island, which is undated but much younger, produced small amounts of cinders and lava in the area of the breached caldera at Kanapou Bay (Macdonald and Abbott, 1970). The likelihood of a future eruption on Kahoolawe seems very low, but if an eruption should occur, it probably would produce a small amount of ash and lava in the Kanapou Bay area.

LANAI

Lanai also is a single shield volcano (fig. 22.13). Potassium-argon ages of lava flows reported from the island range from about 1.46 million years before present (Bonhommet and others, 1977) to 700,000 years before present (Naughton and others, 1980). More recent volcanism has not been recognized, and the likelihood of future eruptions on Lanai seems to be extremely low.

MOLOKAI

The Island of Molokai is formed chiefly by two large volcanoes, both of which are more than 1 million years old on the basis of potassium-argon ages (McDougall, 1964; fig. 22.13). The Kalaupapa Peninsula, which projects 4 km from the north side of the island, is a younger lava cone. Stearns and Macdonald (1947) noted that the lava flows on the peninsula are locally overlain by gravel which they thought was deposited by a stream graded to a stand of sea level 7.6 m higher than the present. This higher sea level has been dated at 120,000 years before present on Oahu (Ku and others, 1974); thus, the lava flows that form the peninsula seem to be older than 120,000 years before present. Three recent potassium-argon ages on the Kalaupapa lava flows, between 570,000 and 344,000 years before present, support that age assessment (Clague and others, 1982). Another vent appeared, perhaps at about the same time, off the east coast of the island. Explosions initially built a small tuff cone, but they were followed by the extrusion of lava flows (Macdonald and Abbott, 1970, p. 348).

Despite evidence cited above that the lava flows of the Kalaupapa peninsula are more than 100,000 years old, depth of weathering on the flows is less than that on some flows on the southwest flank of Haleakala that are younger than 25,000 years before present. This apparent discrepancy has not yet been resolved.

The probability of future volcanism on Molokai seems extremely low. If eruptions do occur, they probably would originate at vents at or near the Kalaupapa Peninsula or off the east end of the island.

OAHU

The eruptive activity that built Oahu occurred during three major periods. Potassium-argon age determinations on lavas from the shield volcano that forms western Oahu (fig. 22.17) range from about 3.5 to 2.74 million years before present, and lavas from the Koolau Volcano of eastern Oahu range in age from about 2.5 to 2 million years before present (McDougall, 1964). A third eruptive period began not long after 1 million years ago, and intermittent volcanism continued at least until about 30,000 years ago (Gramlich and others, 1971). All the vents active during the youngest period lie southeast of a line between Pearl Harbor and the Mokapu Peninsula (figs. 22.17, 22.18). Some of these eruptions formed such well-known features as Punchbowl and Diamond Head and produced airfall ash, lava flows, and pyroclastic-surge deposits that now underlie parts of the Honolulu metropolitan area. One flow of this period originated at the Sugar Loaf Crater on a ridge about 3 km east-northeast of Punchbowl and extended eastward into Manoa Valley, where it now underlies the University of Hawaii campus and the Honolulu suburb of Moiliili (Stearns and Vaksvik, 1935, p. 158). The ages of these events are not well known. Despite previously reported potassium-argon ages of about 900,000 and 100,000 years before present on the flow, Macdonald and Abbott (1970, p. 269) pointed out that the small amount of weathering and erosion on it suggest an age of only a few thousand years before present. Subsequent age determinations, however, gave ages of 68,000 and 66,000 years before present (Gramlich and others, 1971).
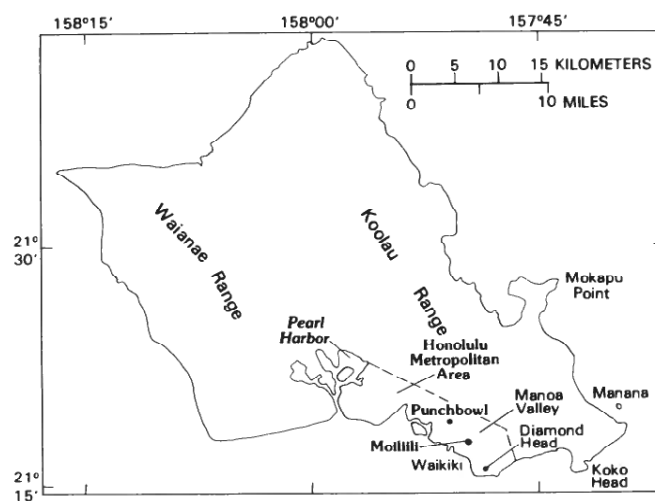

FIGURE 22.17.—The Island of Oahu. The Waianae and Koolau Ranges are each deeply eroded shield volcanoes more than 2 million years old. The most recent eruptions on Oahu originated at vents located between Koko Head and Manana Island.

FIGURE 22.18.—Aerial view southeastward across Koko Crater (center) and Koko Head (right center) on the southeast coast of Oahu. The most recent eruptions on Oahu, between about 43,000 and 31,000 years ago, occurred in the area between Koko Head and Manana Island, which is out of view 4 km to the left of the photograph.

The most recent dated eruptive activity on Oahu, between about 43,000 and 31,000 years ago, was concentrated along the shoreline in the southeasternmost part of the island between Koko Head (figs. 22.17, 22.18) and Manana (Rabbit) Island.

The restriction of the most recent eruptions to that part of the island suggests that if volcanic activity recurs, it will be located in the same general area, although not necessarily at the same vents as before. Eruptions there, if not affected by sea water, probably would produce cindery ash, whose distribution would be predominantly to the west and southwest, and perhaps lava flows. Eruptions in areas at or near sea level, or offshore, probably would be explosive and throw large rock fragments to distances of as much as several kilometers, produce airfall ash that would be carried downwind, and create pyroclastic surges (referred to as lateral blasts by Crandell, 1975). The specific areas that could be affected by these events cannot be predicted now and would not be known until an eruption began.

KAUAI AND NIIHAU

The bulk of the Island of Kauai (fig. 22.1) is formed of lava flows whose potassium-argon ages range from 5.7 to 3.8 million

years before present (McDougall, 1964). The most recent eruptive activity occurred at about 40 vents scattered over the eastern two thirds of the island. These eruptions probably were spread over a long period of time, and all probably are older than 100,000 years before present (McDougall, 1964).

Ages of the lava flows that form Niihau (fig. 22.1) are not known, but even the youngest volcanic rocks on the island are older than the stand of sea level that was 7.6 m above that of the present (Macdonald and Abbott, 1970), and that evidently dates from about 120,000 years ago (Ku and others, 1974).

The absence of any eruptive activity on Kauai and Niihau for more than 100,000 years indicates that the likelihood of future eruptions on these islands is virtually nil.

MITIGATION OF VOLCANIC HAZARDS

Volcanic hazards can be mitigated chiefly by avoiding or controlling the hazards and by minimizing their effects. Hazards can be avoided on a long-term basis by land-use zoning that prevents building of structures in areas of high danger. On a short-term basis, people can be evacuated and some property removed from threatened areas when an eruption is imminent or even underway. Control

of hazardous volcanic events generally is not feasible, although diversion of some lava flows has been at least partly successful. Minimizing effects by protective measures generally is less useful for lava flows than for other volcanic hazards such as tephra and volcanic gases.

Predictions of future eruptions can also help people prepare for and respond effectively to those events. Long-range forecasts can include hazard assessments stating the probable frequency of hazardous events and areas they could affect, based on eruptions of the past. These forecasts can be accompanied by hazard-zonation maps such as those in this report, which show the relative magnitudes of certain hazards in different areas. This information can be used for making decisions regarding both long-term land use and short-term response to eruptions threatened or in progress.

Short-range forecasts are based chiefly on geophysical monitoring that measures the effects, especially earthquakes and deformation, of magma rising into the volcano. Such forecasts probably will provide warning of impending eruptions for most if not all lava-flow eruptions in Hawaii. Premonitory signs of explosive eruptions are less well known, but sudden or major lowering of magma levels, especially at the Kilauea caldera, should be regarded as a strong danger signal.

LAVA FLOWS

Avoidance through land-use zoning and evacuation is virtually the only way to reduce losses from lava flows. Areas in which lava-flow hazard is high can be zoned to restrict use. Even after eruptions have begun, flows can generally be avoided by people, and enough time often is available to remove some property from threatened localities.

Lava flows generally cannot be controlled. Although some diversions of lava flows have been successful, they can raise legal and social problems, and they require favorable conditions.

Diversion or control of flowing lava can be attempted by (1) construction of barriers and diversion channels; (2) use of explosives to block or divert lava streams, including those in lava tubes; and (3) use of water to cool and solidify lava flows. Each of these methods can be temporarily effective, and its success will ultimately depend on an early end to the eruption. The first two methods have been tried in Hawaii with limited success, and diversion barriers have recently been used successfully on Mount Etna in Italy (Lockwood and Romano, 1985). The third method was employed in 1973 at Heimaey, Iceland, and helped prevent destruction of parts of a town and harbor.

Generally, the larger and more rapidly moving the lava flows are, the more difficult it is to control or divert them. Moreover, decisions to attempt to control lava flows should be based on many factors, such as the path and other characteristics of the flow, the type of topography toward which it is moving, the economic and engineering feasibility of control measures, and the social and economic value of areas from which and toward which the lava would be diverted.

BARRIERS AND DIVERSION CHANNELS

Even small obstructions such as rock walls have changed the course of lava flows; thus barriers are an obvious diversion technique. During the 1955 and 1960 Kilauea eruptions, hastily erected barriers temporarily impeded lava flows, although the barriers were ultimately overwhelmed. Theoretically, structures of sufficient size and strength could be constructed to divert lava flows as large as any historic Hawaiian flows. For such barriers to be effective, however, wide and smooth channels would have to be provided as alternate paths. Without such channels, a voluminous flow could thicken behind the barrier and ultimately either overflow or break through it.

Plans have been proposed to protect the city of Hilo by systems of barriers and diversion channels (Jaggar, 1945; Macdonald, 1958, 1962). Their probable effectiveness has been debated (Wentworth and others, 1961), and costs and commitments to existing land use apparently have prevented any such projects from being carried out. The 1975 eruption of Mauna Loa renewed awareness of the lava-flow threat and led to consideration of lava diversion plans (Lockwood and Torgerson, 1980). Technical feasibility is, however, only one of the several difficult aspects of lava diversion. For example, artificial diversion of lava onto property that would otherwise have been spared could lead to complex legal and other problems.

DISRUPTION OF LAVA CHANNELS AND TUBES BY EXPLOSIVES

Attempts were made in 1935 and 1942 to divert Mauna Loa flows by bombing, because of potential threats to Hilo (Jaggar, 1936; Finch and Macdonald, 1949; Macdonald, 1958). It was reasoned that if a lava tube or channel were breached or blocked near its source, the advancing lava front would lose its source of supply, and the flow would halt. Lava issuing from any breach would then have to build a new channel and tube system before a flow would again reach the former front, and during this time the eruption might come to a stop. The bombings of 1935 and 1942 demonstrated the potential of this method, but the eruptions stopped before the method had been fully tested. New plans for use of explosives to divert lava flows were developed after the 1975 Mauna Loa eruption (Lockwood and Torgerson, 1980).

Attempts to divert high-volume, rapid flows might be ineffective, especially those which are not confined to channels or tubes, such as the voluminous flows from the southwest rift zone of Mauna Loa during the early part of the 1950 eruption.

COOLING LAVA FLOWS WITH WATER

During early 1973, lava flows on the island of Heimaey, Iceland, were advancing into the town of Vestmannaeyjar and threatening its harbor. Because a small-scale test indicated that water sprayed on the flow front cooled the lava sufficiently to impede its advance, huge pumps and large quantities of plastic pipe were used to implement the method on a large scale (Williams and Moore, 1973; Einarsson, 1974). As seawater was pumped from the harbor

and sprayed onto the flow, the chilled lava formed a barrier behind which new lava accumulated. The barrier eventually became high enough and strong enough to divert the oncoming lava into a new path, away from the town and harbor.

Such a technique might be feasible in Hawaii on relatively low-volume flows close to sea level. Plastic pipes enabled the water-delivery system on Heimaey to be moved readily in response to changing needs; such pipes, however, could not withstand the high pressures if water were to be delivered more than a few tens of meters above sea level. Even with such limitations, this technique might prove to be valuable under favorable conditions.

Protection from the effects of lava flows, other than by such methods of diversion or control, is generally not feasible. An individual lava flow will have roughly the same effects all the way from its source to its terminus, and attempts to protect buildings and other structures from the hot, crushing lava generally are not effective.

Long-term forecasts of the location of high-hazard areas can facilitate selection, before as well as during eruptions, of areas suitable for various uses, such as relatively safe evacuation routes. In addition, short-term forecasts of eruptions can almost always provide warnings. Even after lava-flow eruptions have begun, time generally is available to carry out evacuation plans.

TEPHRA FALLS

It is not possible to prevent widespread distribution of tephra, but hazard-zone maps can be used for choosing sites for specific uses that avoid areas of high hazard from tephra falls. Even after a tephra-producing eruption has begun, areas sometimes can be evacuated, and its effects can be effectively reduced for people who remain. People close to a vent during a tephra eruption should move upwind of the vent if possible; if they cannot, they should find suitable cover to prevent death or injury from falling fragments. Most other adverse effects can be decreased by placing damp or even dry cloths over noses and mouths to screen out ash particles. Structures in high-hazard zones can be designed to withstand impacts and loads imposed by falling material. In addition, airtight construction and filtering systems can reduce the likelihood that dust-sized particles will infiltrate structures and mechanized equipment.

PYROCLASTIC SURGES

The principal mitigative action for pyroclastic surges is to avoid them. Evacuation must be accomplished, however, before surge-forming eruptions occur, because pyroclastic surges move so rapidly that escape is not possible after they have begun.

Control of surges is not possible, although they can be deflected by natural barriers. Partial protection from the effects of surges is also possible but limited. Structures in areas of high hazard, for example, could be designed to withstand pyroclastic surges typical of Hawaiian volcanoes. Because many surges extend only short distances and become less severe near their margins, the chances of surviving them increase rapidly with increasing distance from the

source vent. The people killed by a probable pyroclastic surge from Kilauea in 1790 were not seriously burned or battered, and they probably died from breathing hot air laden with volcanic gas and ash. People overrun by a pyroclastic surge could improve their chances of survival by finding any shelter, such as a vehicle, to reduce the effects of blast and impact. In addition, use of a filter could be critical because breathing of hot gas and ash is especially dangerous. A wet mask, clothing, or any other material that could filter ash and cool the air inhaled could be especially valuable.

VOLCANIC GASES

Effects of gas can be minimized by selecting building sites in zones of low hazard, and serious short-term effects can be avoided by evacuating some areas during periods of strong gas emission. However, gas probably cannot be completely avoided anywhere on the southern two-thirds of the Island of Hawaii. The emission or distribution of gas cannot be controlled.

For personal safety, topographic depressions near erupting vents should be avoided to eliminate the possibility of being overcome by odorless gases that are heavier than air. Persons with heart or respiratory ailments should avoid areas where concentrations of volcanic gas are possible. A filtering mask or damp cloth held over the face can reduce the effects of sulfur-bearing gas and temporarily lessen discomfort (see Wilcox, 1952, p. 443). No method is known, however, to eliminate gas damage to vegetation and mechanical equipment.

GROUND FRACTURES AND SUBSIDENCE

Ground-fracture and subsidence hazards to people or structures can be avoided only by staying away from areas in which they might occur, for the hazards cannot be controlled and generally cannot be economically minimized. The minor danger to people represented by these hazards can generally be avoided by using care in the areas affected. People living or working in fracture- and subsidence-prone areas should be wary of large open cracks, especially when leaving established trails or in heavily vegetated areas. Damage to structures rarely is catastrophic, but fractures with differential movements of more than a few tens of centimeters, or significant tilting from subsidence, could destroy some buildings. Thus, facilities that have unusual value or that are essential to public health and safety should not be built in areas where these hazards are high. Structures could be designed to resist fractures, but design to resist effects of tilting or submergence from subsidence probably is not economically practical.

The frequency of ground fracturing and subsidence and the localities that are susceptible can generally be predicted, and specific sites could be studied to determine the local magnitude of hazard.

EARTHQUAKES

Potential damage from strong earthquakes is widespread in

Hawaii and cannot be avoided, especially on the Island of Hawaii, but future damage could be reduced by land-use zoning and by earthquake-resistant design and construction. Areas can be avoided that are on or near steep slopes that could fail during earthquakes. Some areas that are underlain by materials susceptible to ground failure during earthquakes are shown on maps (Buchanan-Banks, 1983). Similarly, some areas could be identified in which structures could be damaged by the amplification of ground motion during earthquakes. Construction in such areas can be regulated by zoning or other measures where appropriate, and structures can be designed to resist damage from future earthquakes. Assessments of the magnitudes and frequency of future earthquakes, and of effects of past earthquakes (see Buchanan-Banks, chapter 44, and references therein), can contribute to decisions regarding appropriate future land-use and building requirements.

TSUNAMIS

Zoning to avoid tsunamis would require restricting land use along all the coastlines of the Hawaiian Islands, areas that are now intensively utilized for commercial, residential, and recreational purposes. Nevertheless, avoiding tsunamis through site selection for critical facilities, tsunami-resistant construction, and evacuation plans all could be effective for minimizing future losses. Zoning, for example, could restrict land uses along the coasts to those judged to be compatible with the tsunami hazard, and structures can be designed to resist the forces from tsunamis of predicted size. In addition, tsunami warnings often can be made in time to evacuate threatened coastal zones.

At present, the International Tsunami Information Center in Honolulu is alerted whenever potentially dangerous waves are generated by an earthquake anywhere in the Pacific region, and warnings are issued when appropriate. Low-lying areas generally can be evacuated before tsunamis from distant sources arrive. Tsunami-hazard zones on most islands are shown in telephone books in Hawaii, and people could choose in advance what routes to use in leaving threatened areas. People should be aware, however, that tsumanis could conceivably extend beyond some of the zones shown in telephone books, and they should be prepared to move farther inland or to higher ground if a large tsunami is predicted.

If a tsunami were generated locally, time might be too short for an official warning to be effective. Thus, any earthquake strong enough to make standing difficult can be taken as a warning that a tsunami may soon follow, and people along shorelines should immediately move inland or to higher ground.

FUTURE VOLCANIC ACTIVITY

Future eruptions can be expected at several volcanoes in Hawaii, and they will occur most frequently at Kilauea and Mauna Loa. The historical record suggests that no more than about 5 years will elapse without an eruption at one or the other of those two (Klein, 1982). Lava will be emitted chiefly from vents in the summit areas and along rift zones, but almost all parts of both volcanoes can be affected by lava flows. Based on historical records, about 5–10 percent of Kilauea and Mauna Loa could be covered during any 50-year period. Although wide fluctuations can be expected in eruptive rates from one decade to another, the overall rates likely will remain about the same. It is not possible, however, to predict where the next eruptive centers will be, how frequent or copious eruptions will be in a specific area, or which specific areas will be covered by lava.

The volcanic activity along Kilauea's east rift zone in historical time illustrates a difficulty in using the short historical record to predict future activity in a specific area. Between 1800 and 1950, approximately 2 percent of the eastern flanks of the volcano had been covered by lava from the east rift zone. In 1950, the probability based on these figures that a site in that region would be covered would have been 0.013 percent per year. However, between 1950 and 1975 about 8 percent of Kilauea's east flank was covered by lava, and so the coverage in that interval was actually about 0.32 percent per year. Estimates of future coverage may be no more accurate.

Mapping and dating of prehistoric lava flows also show that rates of burial have also varied widely in recent prehistoric time on both Kilauea and Mauna Loa. Overall rates of burial have changed markedly on Mauna Loa since 1868 (Lockwood and Lipman, chapter 18; Lipman, 1980); areas of high burial rates have switched from one flank of Kilauea to another at various times within the last 500 years (Holcomb, chapter 12; Holcomb, 1979). Accurate predictions of short-term probabilities of lava-flow coverage for any specific area clearly are not yet feasible.

Although lava flows are the most common volcanic hazard on Mauna Loa and Kilauea, explosive eruptions almost certainly will occur in the future. Two large explosive eruptions that produced pyroclastic surges have occurred within the last 2,000 years (Decker and Christiansen, 1984), and another in the future is a distinct possibility. While the hazard from such eruptions may seem small because of their infrequency, the potential threat to life should not be ignored.

Accurate statements of probabilities for frequency of eruptions or rate of burial by lava at Hualalai are not yet possible. However, at least four major eruptions have occurred at this volcano in the last 1,000 years (Moore and others, chapter 20; Moore and others, 1979). The lava flows from Hualalai in 1800–1801 were voluminous and highly fluid, but late prehistoric explosive eruptions near the summit built many large cinder and spatter cones. Future eruptions likely will originate both in the summit area and along the northwest and southeast rift zones, and some areas downslope from active vents will be buried by lava flows.

Neither Mauna Kea nor Kohala has been active during man's occupation of Hawaii. Mauna Kea has erupted within the last 5,000 years, however, most recently about 3,600 years ago (Porter, 1973), and it probably will erupt again. Future eruptions of Mauna Kea will probably be accompanied by mild to moderate explosive activity, producing ash and cinders that will build cones similar to those on its summit area and upper flanks, and produce ash deposits adjacent to the cones. Ash from such eruptions might drift for tens of kilometers downwind. If lava flows were erupted, they probably

would be relatively viscous and thick and would not travel more than a few kilometers from their sources. All the most recent eruptions have occurred at elevations above about 2,000 m, and future activity on Mauna Kea would most likely also originate on the upper part of the mountain.

Kohala is less likely to erupt in the near future than is Mauna Kea. The youngest flow of Kohala, a single flow that occurred long after the major growth of the volcano, has been dated at about 60,000 years before present (McDougall and Swanson, 1972). The probability of future activity of this volcano is very low compared to that for other volcanoes on the Island of Hawaii.

On Maui, Haleakala Volcano has been quiet for nearly two centuries, yet the inferred average rate of eruptions on the volcano as a whole has been nearly 1 per 100 years during the last 1,000 years (Crandell, 1983). This eruptive history suggests that an eruption could occur somewhere on Haleakala within the next 100 years. Recent eruptions have been most frequent within the crater and along the southwest rift zone, so one or the other of these areas seems to be the most likely location of the next eruption, but there is as yet no way to predict its specific time or place.

Future eruptions on Oahu and other islands are possible, but are likely to be so infrequent and scattered that preparation for such eruptions does not seem warranted now.

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